AFRL-PR-WP-TR-2000-2063

INDUCED VOLTAGE SELF-EXCITATION FOR A SWITCHED-RELUCTANCE GENERATOR

EXPERIMENTAL VERIFICATION OF CONCEPT

DR. THOMAS A. LIPO
VELIMIR NEDIC

UNIVERSITY OF WISCONSIN—MADISON
750 UNIVERSITY AVENUE
MADISON, WI 53706

MARCH 2000

FINAL REPORT FOR 08/01/1998 – 09/01/1999

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

PROPULSION DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7251

NOTICE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

Edward B. Durkin

EDWARD B. DURKIN
Mechanical Engineer
Power Generation & Thermal Branch

Scott Rubertus

SCOTT RUBERTUS
Chief
Power Generation & Thermal Branch

FOR THE COMMANDER

Jerry E Beam 6-28-00

JERRY E. BEAM
Acting Chief, Power Division

Do not return copies of this report unless contractual obligations or notice on a specific document requires its return.

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	MARCH 2000	FINAL REPORT FOR 08/01/1998 - 09/01/1999

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
INDUCED VOLTAGE SELF-EXCITATION FOR A SWITCHED-RELUCTANCE GENERATOR -- EXPERIMENTAL VERIFICATION OF CONCEPT	C F33615-98-C-2867 PE 62203 PR 3145 TA 01 WU C9
6. AUTHOR(S) DR. THOMAS A. LIPO VELIMIR NEDIC	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF WISCONSIN--MADISON 750 UNIVERSITY AVENUE MADISON, WI 53706	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) PROPULSION DIRECTORATE AIR FORCE RESEARCH LABORATORY AIR FORCE MATERIEL COMMAND WRIGHT-PATTERSON AFB, OH 45433-7251 POC: ED DURKIN, AFRL/PRPG, 937-255-6241	10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-PR-WP-TR-2000-2063

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED.	

13. ABSTRACT *(Maximum 200 words)*

The switched-reluctance machine (SRM) is a promising candidate as a motor/generator for USAF power applications. The simple, non-wound laminated rotor allows high rotating speeds while the separate phase windings are conducive to fault-tolerant operation. The SRM, however, is a passive electromachine that requires external electric power to energize its controller and stator windings during its start-up for power generation. One means to excite the machine in a "self-starting" mode is to attach permanent magnets to the machine stator, so that rotor rotation will cause the magnet's field to induce electric current within a nearby stator winding. This current can then be used to charge the DC-link capacitors that energize the control switches and all phase windings. This research program was an experimental effort to verify a self-excitation concept developed as a computer model by the University of Wisconsin. A small SRM rated at 240 V, 1 HP, & 4000 rpm speed was modified to use three different configurations of a magnet installed between a stator pole and its windings. Experimental results include the charge-up times for a DC-link capacitor connected in circuit to the motor.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Electric Power Generation, Motors & Generators	27
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

TABLE OF CONTENT

1. INTRODUCTION

Switched reluctance (SR) machines have been found to offer important advantages over conventional AC machines in generating as well as motoring applications. For example, phases of the switched reluctance machine are decoupled from each other under normal operation thereby improving reliability. This characteristic offers an advantage over more conventional machines (PM machines primarily) when the machine is used as a generator, since the faulted phase will not conduct current while the remaining phases continue to operate. However, the primary problem concerning effective employment of switched reluctance generator is the fact that such a machine is inherently completely passive and has no self-excitation capability so that some other source of power is necessary for excitation which consequently increases complexity and decreases reliability.

Computer simulations of a new self excitation principle using a small permanent magnet were conducted in a previous study for WPAFB [1,2]. These simulations have demonstrated that permanent magnets could be placed on a portion of the axial length of two poles of the switched reluctance machine to provide its excitation requirements during starting. In general, SR generator power is fed to a power controller and from there to a DC link capacitor. The change of the permanent magnet flux during the rotation of the rotor induces alternating voltages in the stator windings which can be rectified and which will initially charge the DC link capacitor to a small voltage. Once excitation is supplied to the generator for a brief period using the energy stored on the link capacitor, the capacitor voltage can be built up to the rated voltage by extracting energy from the prime mover.

In general, the magnets can be placed in various positions in the magnetic flux path and may have various sizes and shapes. The simulation results have shown that the required amount of the permanent magnet flux can probably be obtained by simply fixing the rectangular magnet pieces to each tooth of the machine poles. The purpose of this study is to experimentally verify the utilization of the permanent magnets in self-exciting a switched reluctance generator and to determine the minimum amount of the required permanent magnet flux. In order to accomplish this task, a switched reluctance machine drive complete with the affixed permanent magnets and a power electronic controller have been implemented.

2. SWITCHED RELUCTANCE GENERATOR

2.1 Switched Reluctance Machine Used

A commercially available switched reluctance machine was used for the experimental set-up. This is four-phase regular 8/6 machine with eight stator poles and six rotor poles. General characteristics include:

- Mounting: NEMA 48C Face Mount

- Power Output: 1 HP at 4000 RPM continuous, 1.3 HP intermittent
- Rated Voltage: 240 Volts
- Efficiency: 82% at 1 HP, 4000 RPM.

The switched reluctance machine employed is supplied with a magnetic commutator mounted on its shaft. This commutator is simply a magnet ring with magnetic poles oriented radially whose magnetic transition gives exact information of the rotor position. Such a magnetic encoder is suitable for use with Hall-effect sensors and simplifies the overall control circuit design.

A cross section of the machine stator and rotor core is shown in Figure 2.1. The picture shows also the permanent magnet pieces affixed to each pole of the one stator phase, according to the proposed option. Manufacturer's data for the machine are provided in the Appendix.

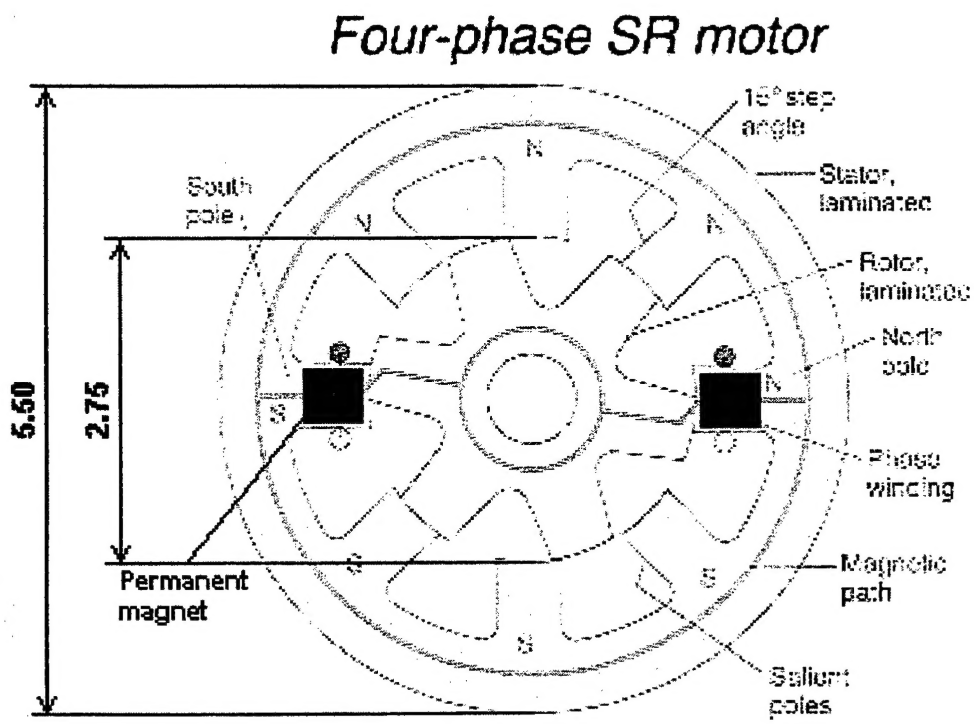

Figure 2.1: *Cross section of the switched reluctance machine with permanent magnets affixed to two stator poles*

2.2 Self-excited Generator Design

As demonstrated in the previous computer simulation study, self-excitation capability of the SR generator could potentially be obtained by fixing the rectangular magnet pieces to each pole of the machine phase. This concept was implemented in three different means which will be shown and explained in the remainder of the text.

The permanent magnet material used is samarium cobalt #26 with the following specifications:

- Residual Flux Density: 10500 Gauss
- Coercive Force 9200 Oersteds
- Maximum Energy Product 26 MGOe
- Maximum Operating Temperature 350 °C.

The demagnetization curve for the permanent magnet material is provided in the Appendix. The dimensions of the particular magnet piece were chosen to fit the dimensions of the stator tooth. The shape and the dimensions of one permanent magnet piece are shown in Figure 2.2.

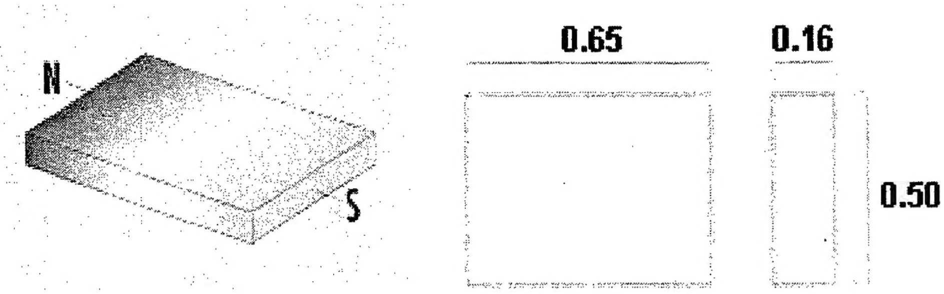

Figure 2.2: *Shape and the dimensions of the used permanent magnet pieces*

The first option of magnet placement that was implemented is shown in Figure 2.3. In this case, the stator core was cut around the teeth of the one phase from top surface toward bottom of the core. Several lamination layers of each tooth were removed and room for the permanent magnets was provided. The permanent magnets were placed so as their top surfaces were aligned with the surface of the stator core. This was done on both sides of the stator core with four permanent magnet pieces (two permanent magnets per phase tooth on both stator sides) employed. The mounted permanent magnets can be clearly seen in Figure 2.3 which shows only one side of the stator core.

The second option that has been implemented comprises only permanent magnets fastened to the stator poles without cutting the stator core. The permanent magnet pieces were affixed in the available space between the stator winding and the pole tooth. Again, four permanent magnets were used, two pieces on both sides (top and bottom) of each phase pole.

The last option for a self-excited SR generator design was similar to the previous one. The difference is that only two instead of four permanent magnet pieces were fastened on each phase tooth on only one side of the stator core. This arrangement is illustrated in Figure 2.4.

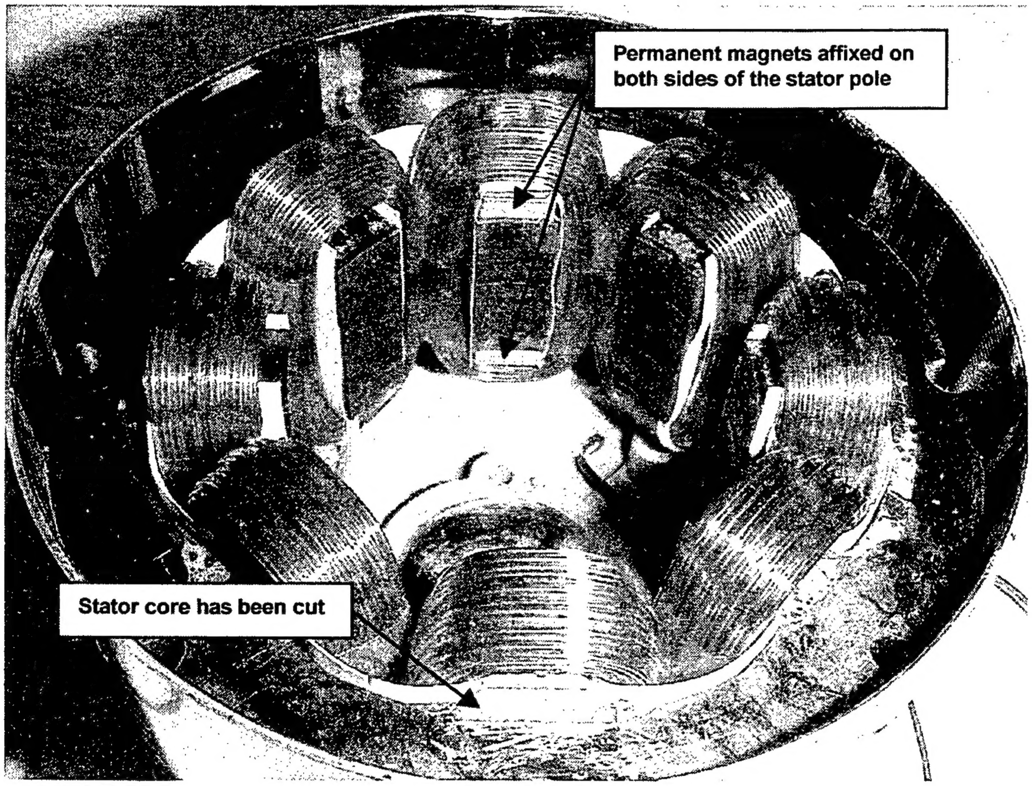

Figure 2.3: *Self-excited generator design for which stator teeth have been cut*

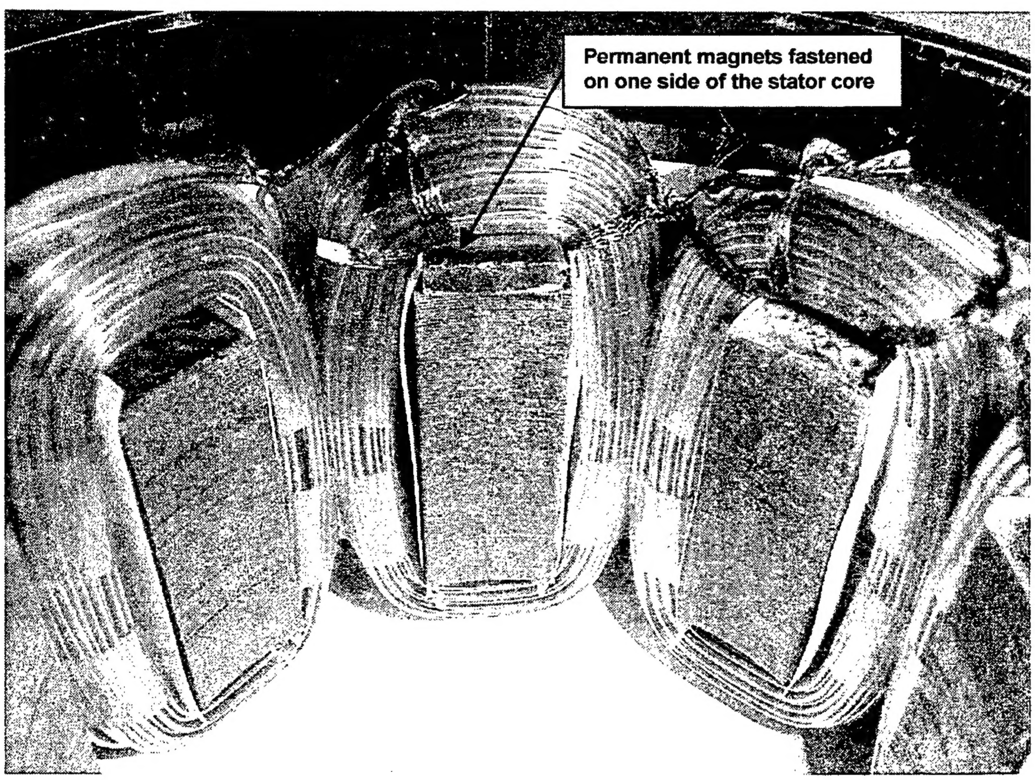

Figure 2.4: *Self-excited generator design implemented without cutting the stator core*

Additional pictures of the proposed self-excited switched reluctance generator from various spatial positions are included in the Appendix. Normally, the strength of the permanent magnet flux that is closed through the stator and rotor core and the air gap depends on the position of the permanent magnets with respect to the rotor core. Therefore, to maximize the magnet flux, the permanent magnet pieces were placed to minimize the air gap between the permanent magnets and rotor core as much as it is possible in all of the above mentioned options.

3. POWER ELECTRONIC CONTROLLER

The power electronic controller for the switched reluctance generator can be regarded as comprising the power converter and control circuitry. Although SR generators are simple machines in principle (they don't need the brushes or magnets typical of DC generators), they do require rotor position sensors and electronic commutation. The power controller must feed the machine with current precisely phased relative to the rotor position. Therefore, the drives consist of more complex circuitry to provide DC power and solid-state switches that synchronize stator phase-winding pulses with rotor position-sensor signals.

3.1 Power Converter Circuit

The direction of the switched reluctance machine torque depends only on the sign of $dL/d\theta$ (the rate of change of inductance with rotor position). The machine is capable continuously regenerating when the firing angles arrive after the aligned position, i.e. when $dL/d\theta < 0$. The advantage of torque production with this machine compared to PM machines is that the flux-linkage and current may be unipolar.

Although the power converter circuit has to supply only unipolar current pulses, it must also be capable of applying pulses of reverse voltage and of absorbing the returned power. A number of different circuit topologies may be used to drive switched reluctance generators. Regardless of the number of switches per phase, the common characteristic is that there must be a freewheeling path for the phase current. Usually, the reverse voltage is connected to the phase winding through freewheeling diodes.

The converter configuration of the Figure 3.1 was chosen for this self-excited switched reluctance generator. This controller circuit with two MOSFET transistor and two diodes per phase provides the maximum control flexibility and efficiency, with minimum passive elements. In addition, the body diodes of MOSFET switches establish a full bridge diode rectifier resulting in shorter charging time of the DC link capacitor. This circuit operates in the single-pulse mode with a current-regulated control loop.

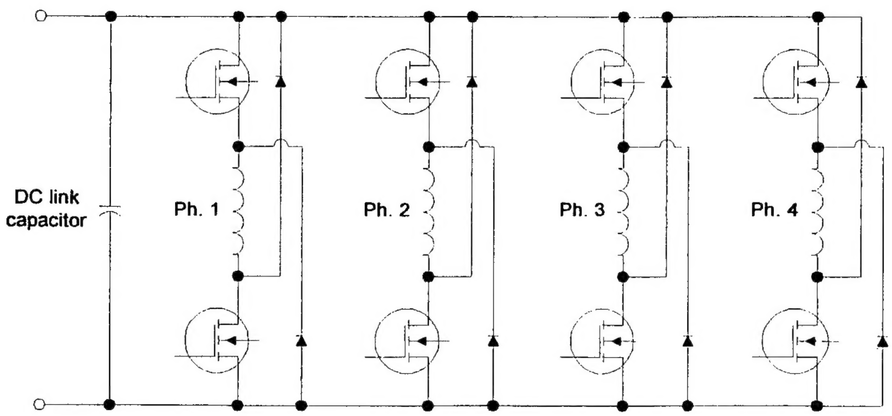

Figure 3.1: *Power converter circuit*

The converter has three different operating modes: charging mode, voltage build-up mode and generating mode. In charging mode, the DC link capacitor is charged by the alternating emf of the permanent magnet flux through the diode rectifier circuit. The power converter operates completely passively in this mode of operation. The passive diode circuit rectifies the induced voltage of the phase where the permanent magnets are placed. The DC link capacitor is charged up to the peak value of this induced emf (minus diode forward voltage drop). This voltage may be few volts depending on the machine speed and permanent magnet flux power. The Figure 3.2 illustrates the corresponding waveforms of this mode of operation.

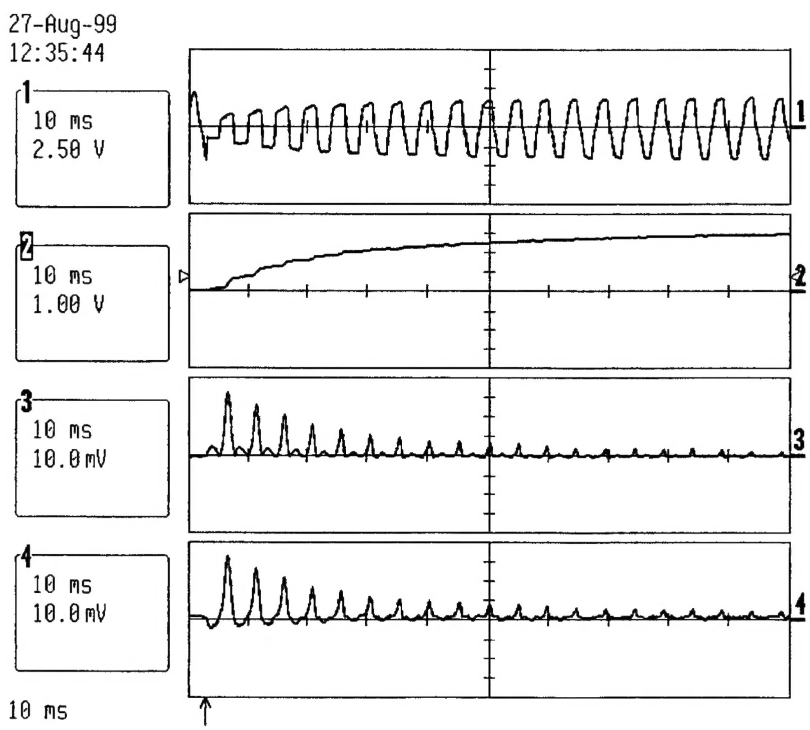

Figure 3.2: *Waveforms during the charging mode of operation. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and charging current, and phase current. The scale for the bottom two traces is 0.2A/div.*

During the voltage build-up mode the capacitor voltage is increased up to the rated voltage. This is accomplished by actively switching of the power transistors. The switching action is similar to the regular generating mode, except that a duty-cycle which is too lengthy may completely discharge the capacitor when its voltage is still fairly low. In general, the excitation power is first supplied from the DC link capacitor while the transistors are conducting. The DC link voltage turns on at a point near the aligned position (slightly before or after) so that the bulk of the winding conduction period comes after the aligned position. Current begins to rise as the rotor poles approach the stator poles of the next phase to be excited. The phase current increases utilizing the energy from the capacitor until the switches are turned off at the commutation angle defined by the control circuit.

When the switches are turned off, the current in the switches is commutated to the diodes and continues to flow until it reduces to zero. The terminal voltage reverses which is also handled by the freewheeling diodes. Generating power is now returned to the DC link capacitor during this de-fluxing period. Therefore, the direction of the energy flow is changed from the machine to the capacitor and hence, the capacitor voltage increases. The Figure 3.3 illustrates the waveforms of the voltage build-up mode when only one generator phase is excited. The harmonic spectrum of the alternating emf induced by the permanent magnet flux is shown in Figure 3.4.

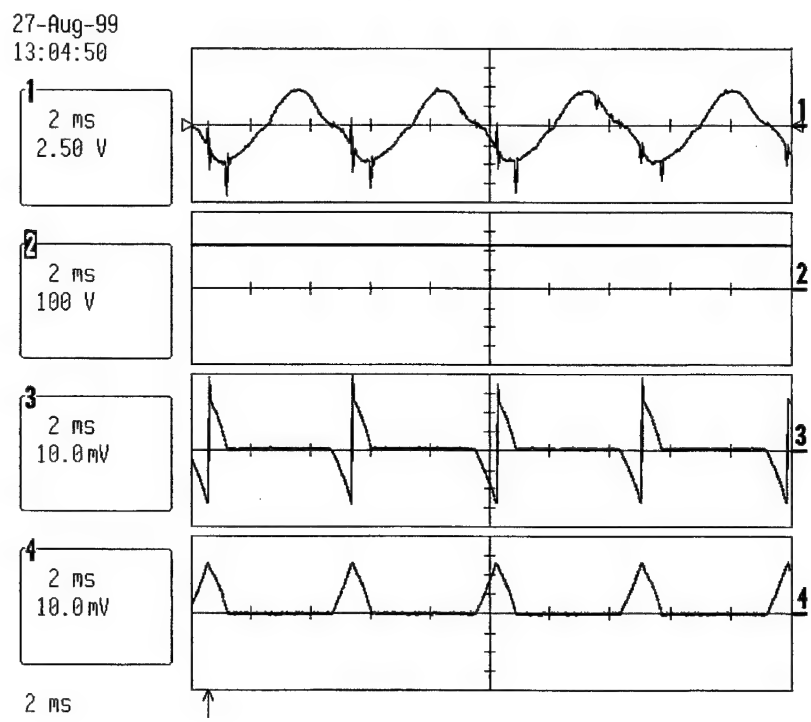

Figure 3.3: *Waveforms of the voltage build-up mode of operation. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and current, and phase current. The scale for the two bottom traces is 1A/div.*

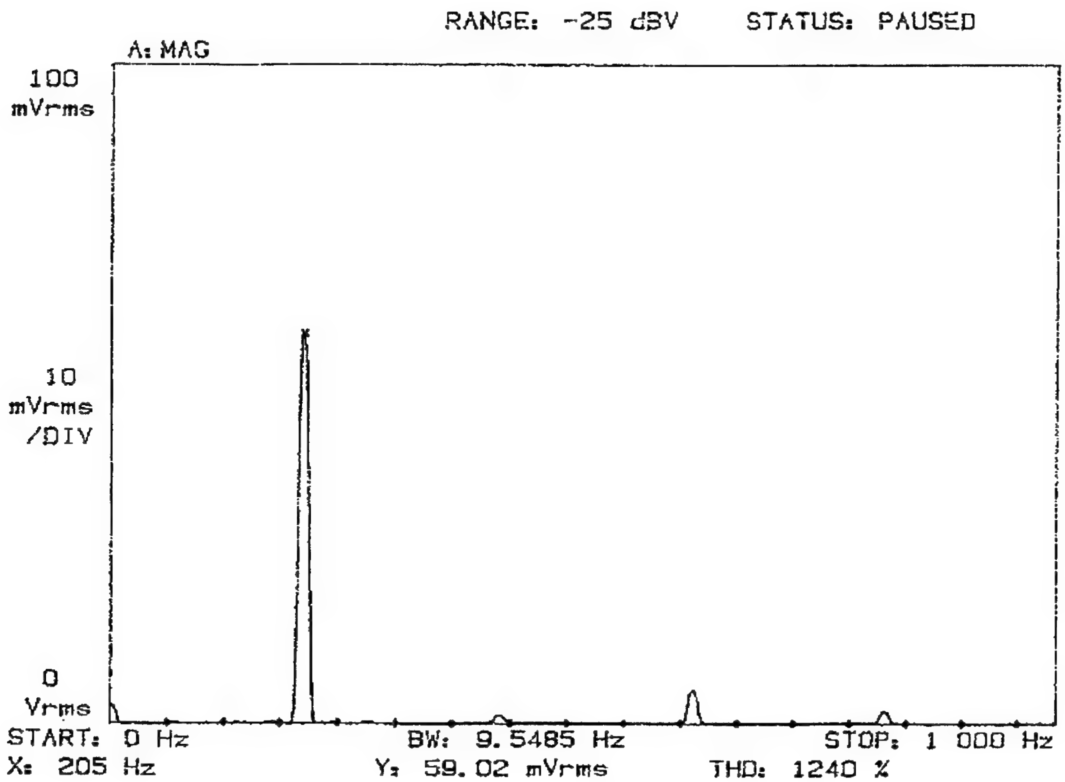

Figure 3.4: *Harmonic spectrum of the induced alternating voltage*

For generator action to be sustained as well as produce a voltage increase during the build-up mode, the energy returned during the de-fluxing period must exceed the excitation energy supplied when the switches are on. The difference between electrical input energy and electrical output energy is provided by the prime mover. The amount of energy flow can be controlled by regulating the turn-on instants of the switches.

3.2 Control System

The power controller can be considered as a block whose input is the generator voltage reference and whose output is the generator excitation current. As already has been mentioned, the control circuitry is the part of the controller which ensures that the generator excitation pulses, delivered by the power converter circuit, have proper timing and duration.

In order to drive this self-excited switched reluctance generator, a control system was designed consisting of position sensing elements, synchronization circuitry, commutation logic and PWM generators. The block structure of this control system is shown in Figure 3.5. The position detection block of this figure has been realized by a magnetic encoder. It consists of a magnet ring commutator mounted on the machine shaft and two Hall-sensor ICs. The synchronization and commutation circuits are implemented by several standard CMOS digital chips. PWM generators

are standard analogue current-mode controllers which are synchronized with digital circuitry and with generator voltage reference.

Current-mode controllers have been chosen since they are suitable for the flyback converter structure which can be recognized in the per-phase power circuit. The only fundamental difference is that the inductance is not constant but varies with rotor position.

3.3 Putting It All Together

The structure of the power electronic controller ensures proper driving of the self-excited switched reluctance generator. Each block of the drive system can be recognized in Figure 3.4. As can be noted, each generator phase has its own PWM controller. This makes it possible for the self-excited generator to operate with only one excited phase.

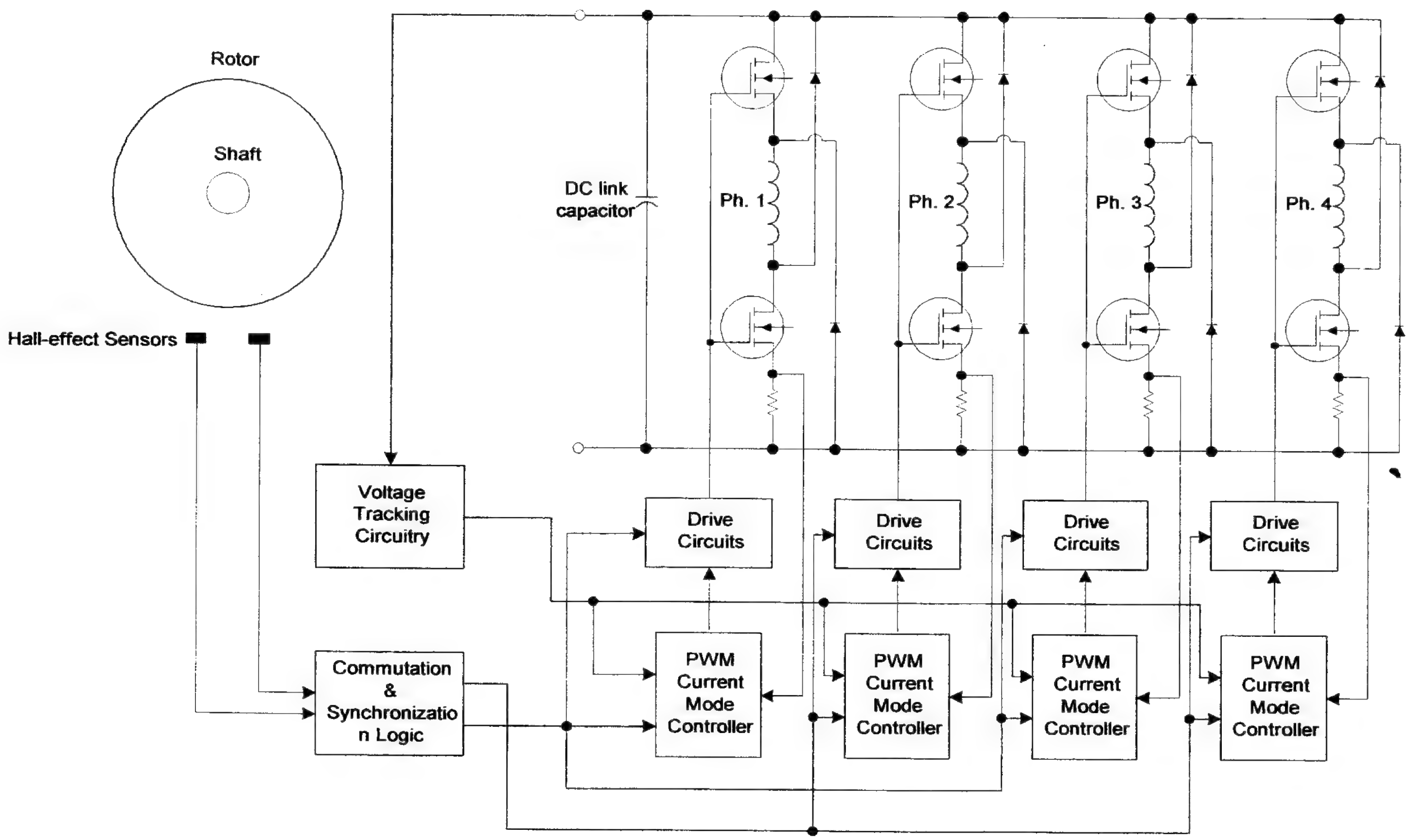

Figure 3.5: *Block diagram of the power electronic controller*

4. EXPERIMENTAL RESULTS FOR CHARGING THE LINK

4.1 No-Load Conditions

The tests were done for three different configurations of the self-excited SR generator described in section 2.2. In all three cases, the DC link capacitor of 680 μF was charged by passive action of the converter circuit at the start. Once the capacitor was initially charged the driving pulses for the active switches were applied by manually presetting the voltage command reference. It should be noted that control system was implemented in open-loop mode without providing a control signal of the DC link voltage. Hence, the DC voltage build up was "open loop" and the process controlled manually by control of the firing pulses. It can be noted that the DC link capacitor voltage readily builds up to the rated value which is 240 V. The machine speed was 2000 rpm, only half of the maximum speed, for each self-excited generator configuration.

Experimental waveforms of the charging operation for configuration #1 are shown in Figure 4.1. Figure 4.2 shows experimental waveforms during the start of the voltage build-up operation for configuration #1.

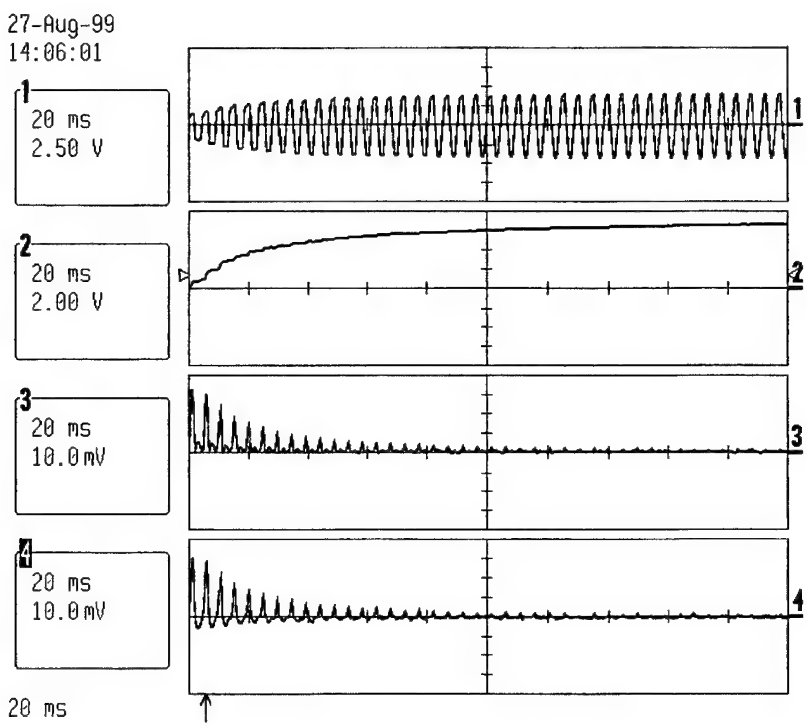

Figure 4.1: *Waveforms during charging mode of operation, configuration #1. The waveforms from top to bottom: induced alternating voltage, capacitor voltage and current, and phase current. The range for the two bottom traces is 0.2A/div.*

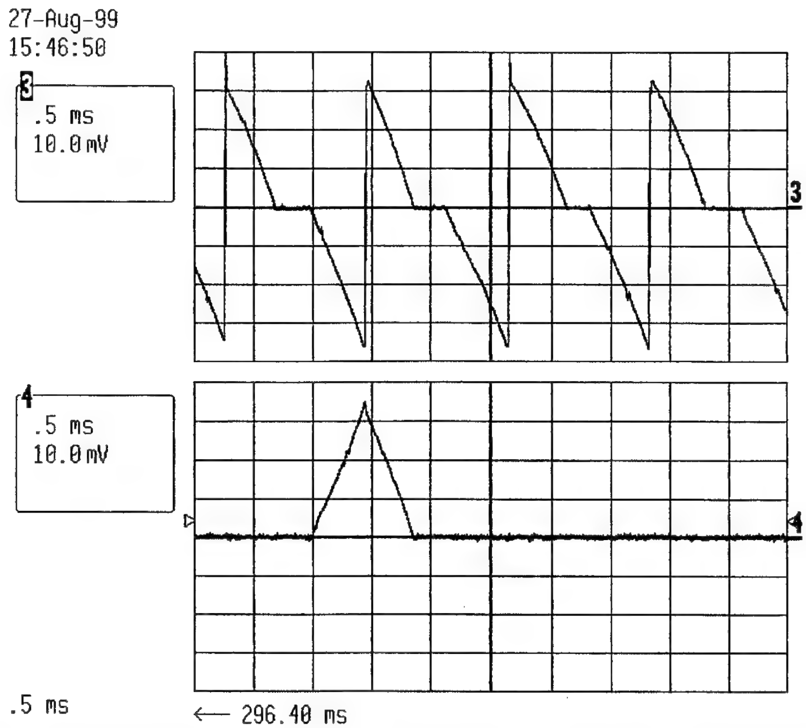

Figure 4.2: *Waveforms during voltage build-up mode of operation, configuration #1. The top waveform is capacitor current and the bottom waveform is phase current. The range for both traces is 1A/div.*

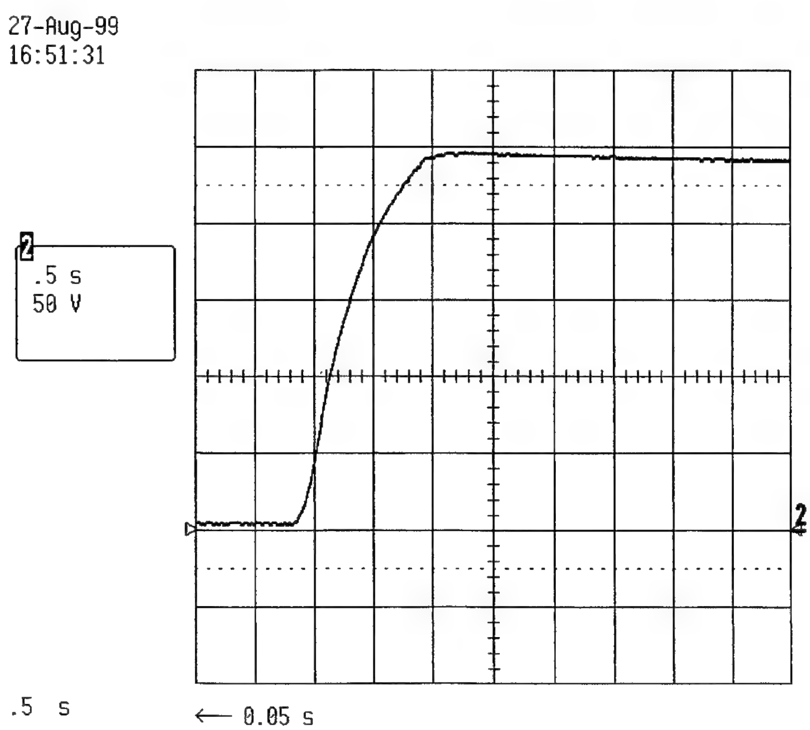

Figure 4.3: *Build-up of the DC link capacitor voltage, configuration #1*

The process of a gradual increase of the DC link capacitor voltage for configuration #1 is shown in Figure 4.3. Charging continues until the capacitor voltage reaches the rated value of 240 V, which lasts less than one second. From Figure 4.3, the changing build-up rate can be recognized. This appears because the DC link voltage command signal is changed manually, as already mentioned. More physical insight of the process could be obtained by referring to Figure 4.4 which shows the same build-up mode, but only during first 200 ms. The natural generator-circuit response, after a step change in voltage command has performed, is shown in this Figure.

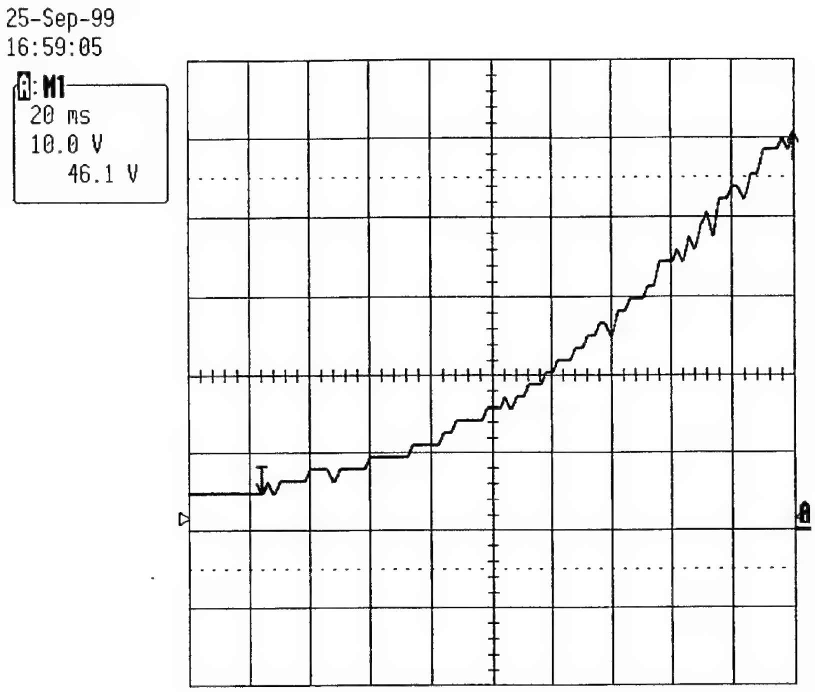

Figure 4.4: *Build-up of the DC link capacitor voltage during first 200 ms*

In practice, faster system response can be achieved by feeding back and regulating the DC link voltage. With a closed-loop control system, it would be possible to achieve automatic duty cycle adjustment, and therefore the machine is supplied with required excitation power. Further, it should be mentioned that this open loop build-up rate is not defined by the current limit setpoint of the current mode controllers in the control circuit rather by the excitation instant during the rotor transition between aligned and unaligned position and circuit itself. By shifting the moment when the gate pulses of the converter switches are applied it is possible to change the excitation and thus generated power which defines the build-up voltage rate.

Finally, the waveforms for the self-excited generator, using configuration #1 when operating in the continuous generating mode are shown in Figure 4.4.

Experimental results for three different configurations of the self-excited SR generator can be summarized by referring to Table 1 which contains corresponding measured results. It can be recalled that configuration #1 was realized with stator teeth that have been cut, configuration #2 is realized without cutting the stator core and with four permanent magnets, and configuration #3

is realized with only two permanent magnets and without cutting the stator core. The amplitude of the alternating voltage induced by the permanent magnets, the DC voltage of the initially charged capacitor and the time to initially charge the capacitor are shown. Again, the machine speed was 2000 rpm in all cases.

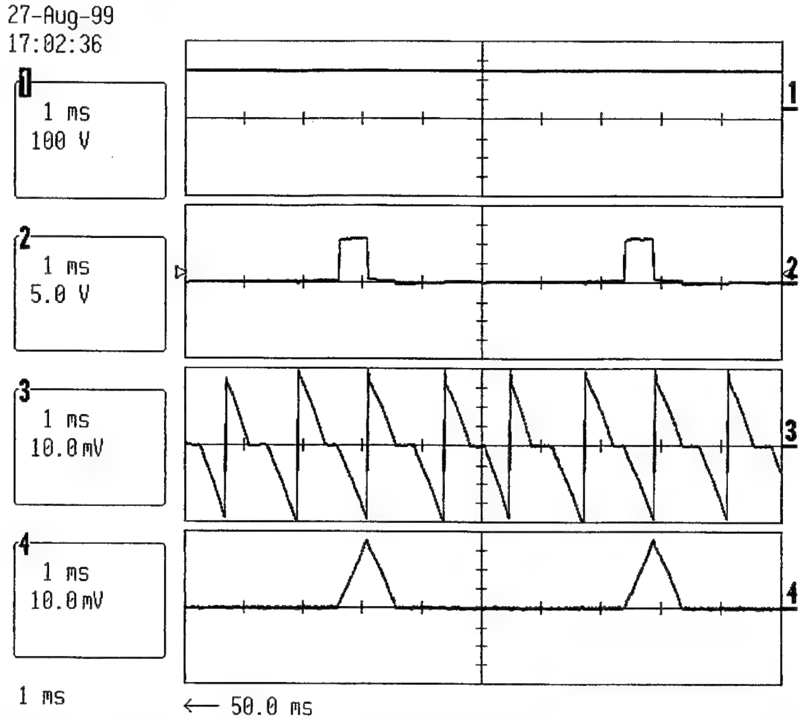

Figure 4.5: *Waveforms during continuous generating mode of operation, configuration #1. The waveforms from top to bottom: capacitor voltage, gate drive pulses, capacitor current and generator phase current. The scale for the two bottom traces is 1A/div.*

Table 1: *Summary of experimental results*

	Zero-to-peak AC voltage [V]	Initial DC voltage [V]	Charge time [s]
Configuration #1	4.36	3.72	0.40
Configuration #2	1.76	1.23	3.22
Configuration #3	1.09	0.71	11.87

The experimental results demonstrate that successful operation of the described self-excited switched reluctance generator is possible. An inexpensive redesign of the standard switched reluctance machine by using the permanent magnet pieces could provide the machine with self-excitation capability. This is especially true for the self-excited generator configuration realized without cutting the stator core and with only two permanent magnets simply fastened onto the phase teeth.

4.2 Resistive Load Case

Tests were done also for various load conditions. So simulate a load, a resistor of 300 Ω was connected to the output of the self-excited generator, across the DC link capacitor terminals. Experimental waveforms for the start of the build-up mode and continuous generating mode are shown in Figures 4.6 and 4.7 respectively.

From Figures 4.6 and 4.7 it can be seen that self-excited generator operates succesfully again, supplying 150 W of output power. As expected, the starting build-up rate is now less than that for the no-load conditions. Further, slightly less (≈ 210 V) steady state generator voltage is obtained, since the current reference in the control circuitry has not been changed.

4.3 Short Circuit Test

Finally, the short circuit condition on generator's DC bus was checked. Experimental results obtained are shown in Figure 4.8. The self excited generator is capable to produce and supply the short circuit current through the passive diode circuit. Once the short circuit conditions were released, the raise of the DC link voltage was possible.

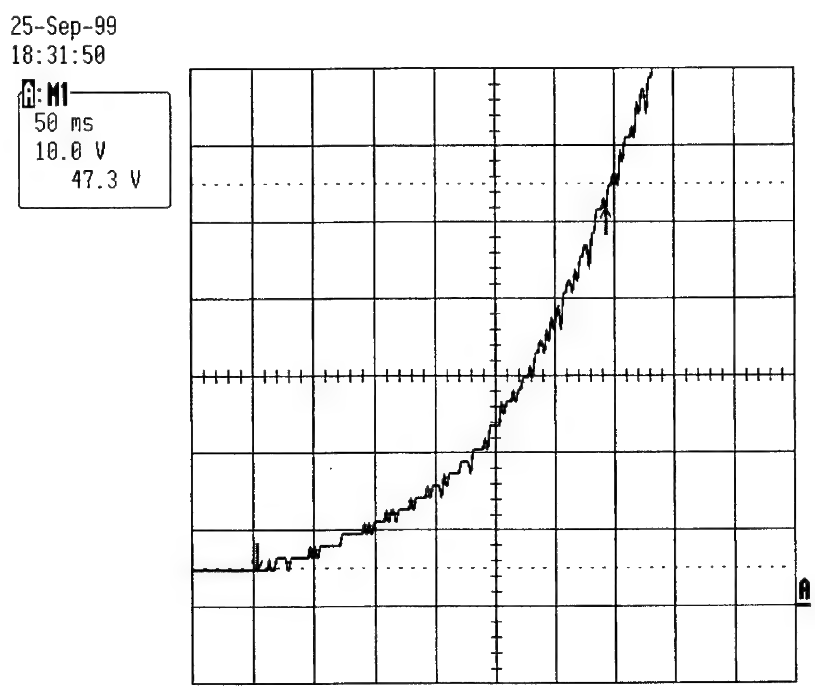

Figure 4.6: *Build-up of the DC link capacitor voltage for the loaded generator*

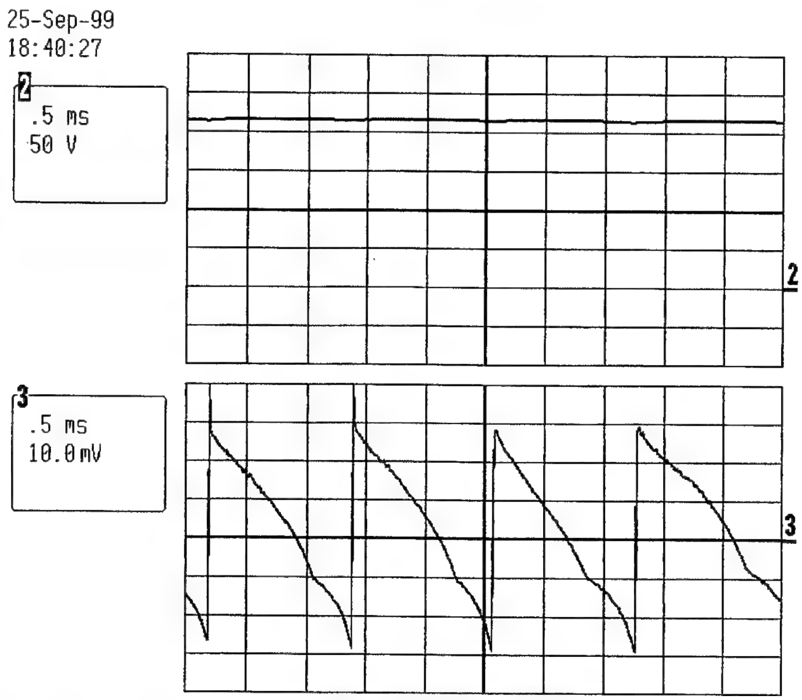

Figure 4.7: *Waveforms during continuous generating mode of operation for the loaded conditions. The top and bottom waveforms are capacitor voltage and current. The range for the current trace is 2A/div.*

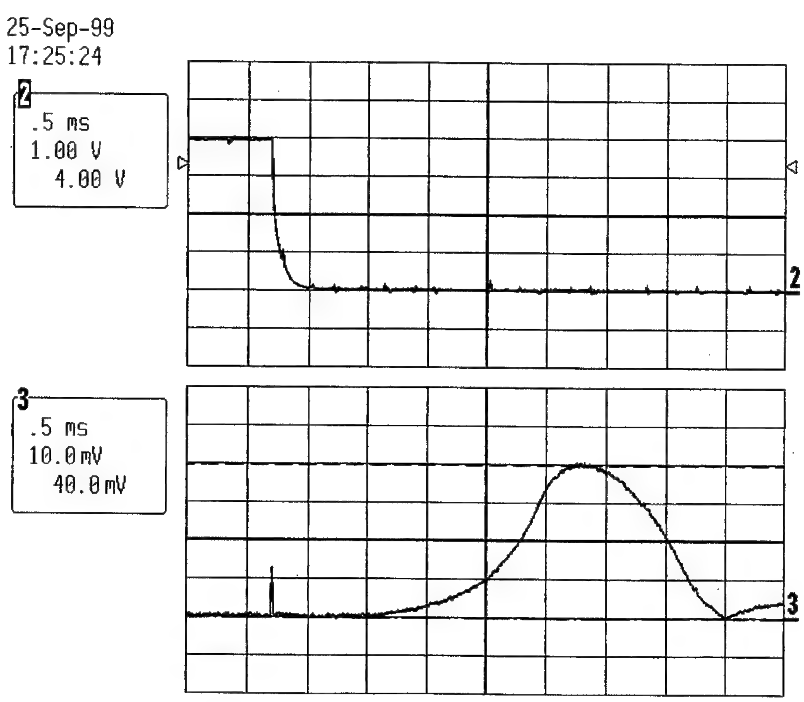

Figure 4.8: *Waveforms during one cycle of the short circuit conditions. The top and bottom waveforms are capacitor voltage and current. The scale for the current trace is 0.1A/div.*

5. CONCLUSION

The purpose of this research project was to experimentally verify the use of the permanent magnets for self-excitation of a switched reluctance generator. While the previous simulation study completed an analytical investigation of this concept, this work extended the investigation to a complete working experimental mode. Tests made have confirmed the validity of the existing computer simulation. In particular, a switched reluctance machine drive complete with affixed permanent magnets and a power electronic controller have been implemented. The tests were done on a small commercially available 1 HP switched reluctance machine. A standard converter configuration with two power transistor and two diodes per phase was chosen for this self-excited switched reluctance generator. The converter control circuit was realized with minimum necessary components making overall design simply and accurate.

It is important to note that the power converter control circuit was implemented in open-loop mode without feedback of the DC link voltage. Instead, a simple reference circuitry was used in the control system. It is reasonable to expect that faster build-up of the DC link voltage can be achieved with a control system when closed-loop control of the DC link voltage is implemented. Such a controller should be readily able to automatically adjust the duty-cycle of the active switches and provide the machine with its required excitation power.

The tests have been carried out for three different configurations of the self-excited switched reluctance generator which are described in the preceding text and for the no-load as well as for the loaded condition. The experimental results have demonstrated that successful operation of the proposed self-excited switched reluctance generator is possible and have confirmed the necessary realism needed to accurately predict the self excitation concept.

The self excitation process was successful even for a self-excited generator configuration realized without cutting the stator core and with only two permanent magnets simply fastened onto the phase teeth. For this configuration, the initial charging of the DC link capacitor was only 0.5 V showing that an inexpensive, reliable modification of the standard switched reluctance machine by using the permanent magnet pieces provides the machine with self-excitation capability.

REFERENCES

[1] T. Matsuo, J. Luo and T. A. Lipo, "The Feasibility Study of a Self Excited Permanent Magnet Generator", Final Report to WPAFB, Oct. 1996.

[2] T. Matsuo, J. Luo, E. P. Hoffman and T. A. Lipo, "Self Excited Variable Reluctance Generator", IEEE IAS Annual Meeting, Oct. 1997, pp. 653-660.

[3] T. J. E. Miller, "Switched Reluctance Motors and Their Control", Magna Physics Publishing and Oxford Press, 1993.

[4] "Practical Considerations in Current Mode Power Supplies", Applications Handbook, Unitrode Corporation, Merrimack, New Hampshire, 1997.

UNIVERSITY OF
WISCONSIN
MADISON

Wisconsin Power Electronics Research Center
(WisPERC)

APPENDIX TO THE FINAL REPORT

THE FOLLOWING ARE INCLUDED IN THE APPENDIX:

- Manufacturer's data for the switched reluctance machine.
- The demagnetization curve for the permanent magnet material used.
- Additional pictures of the proposed self-excited switched reluctance generator from various spatial positions.

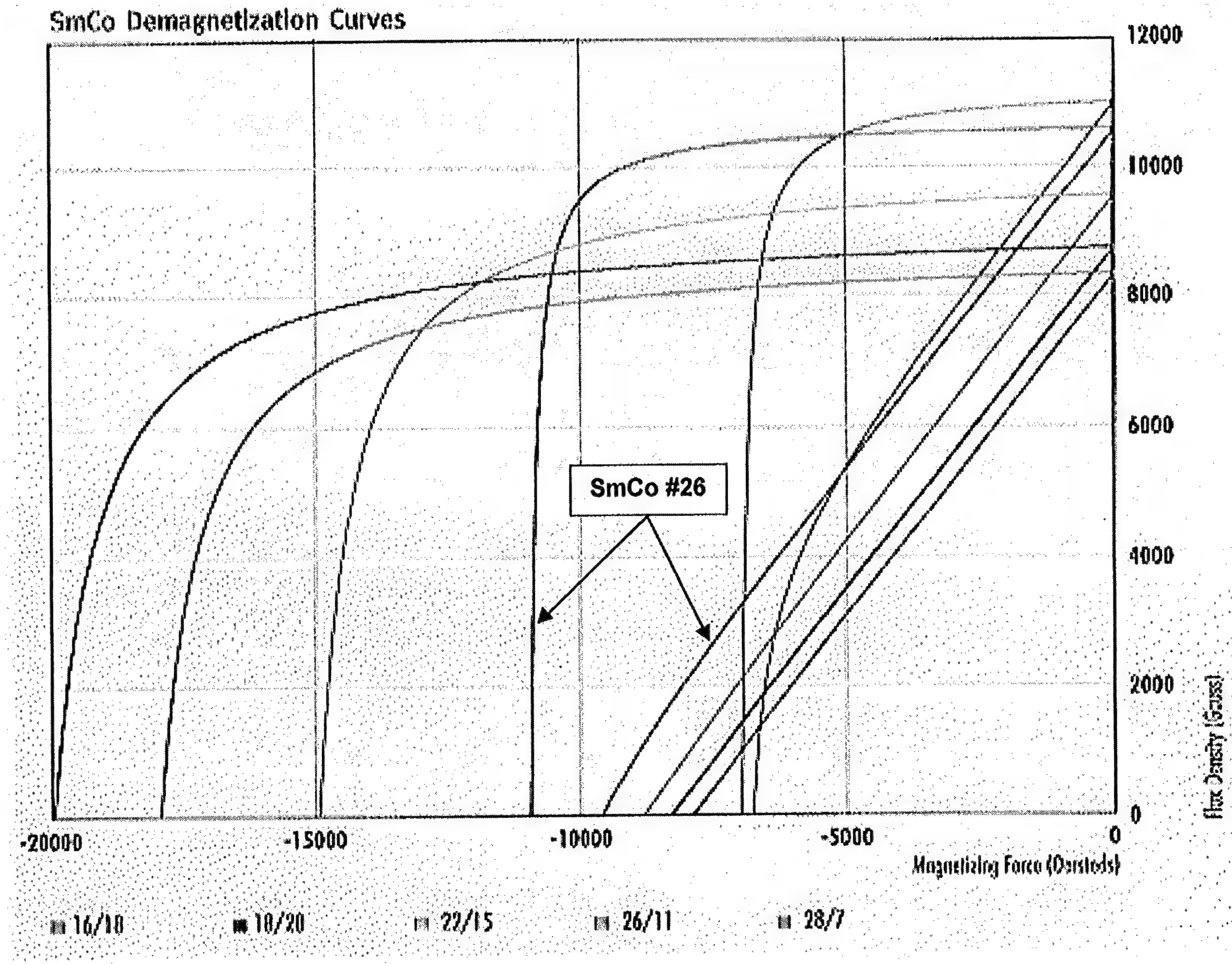

Figure A.1: *Demagnetization curves for the used permanent magnet material - samarium cobalt* #26

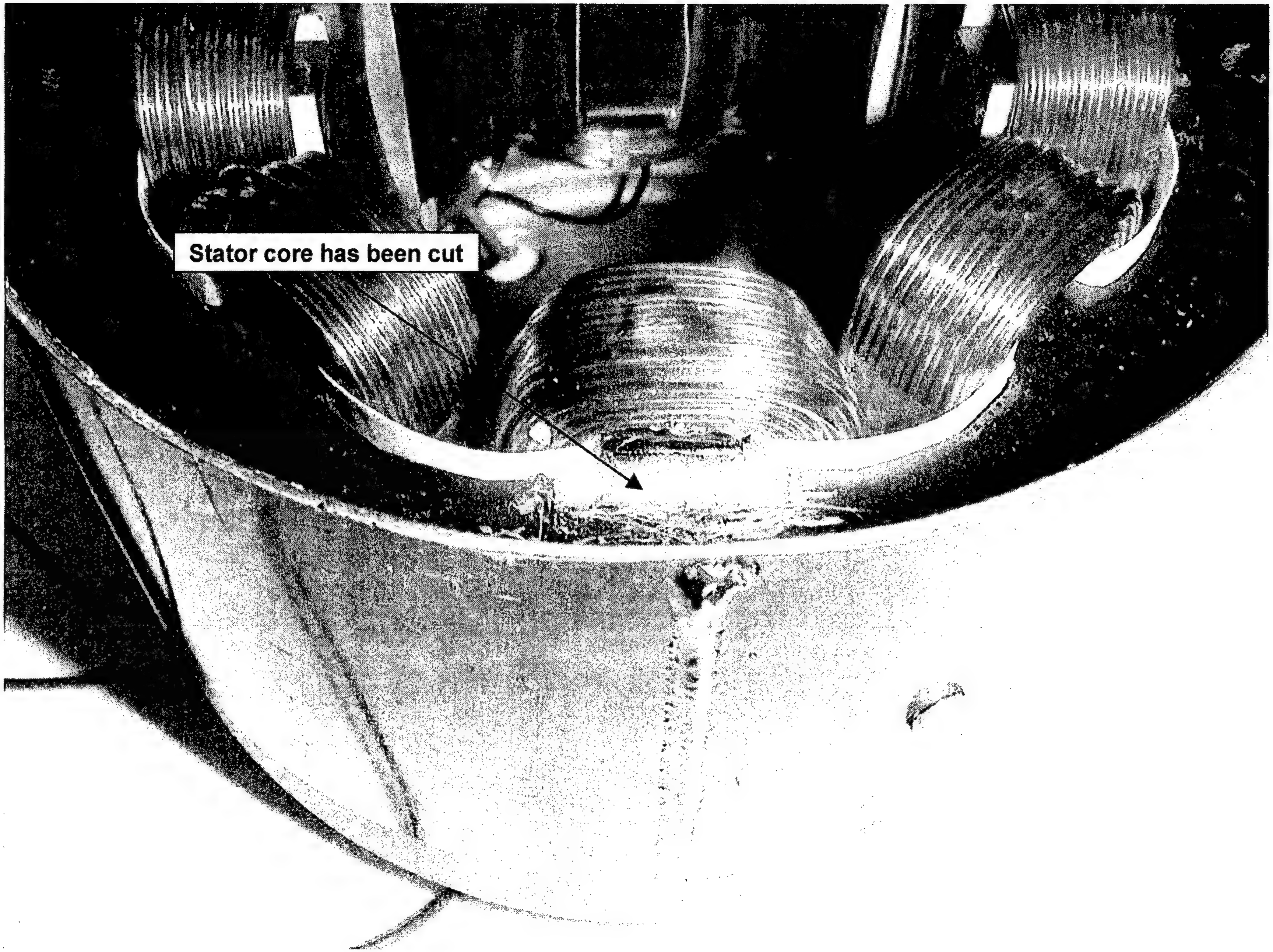

Figure A.2: *Self-excited generator design for which stator teeth have been cut, configuration #1*

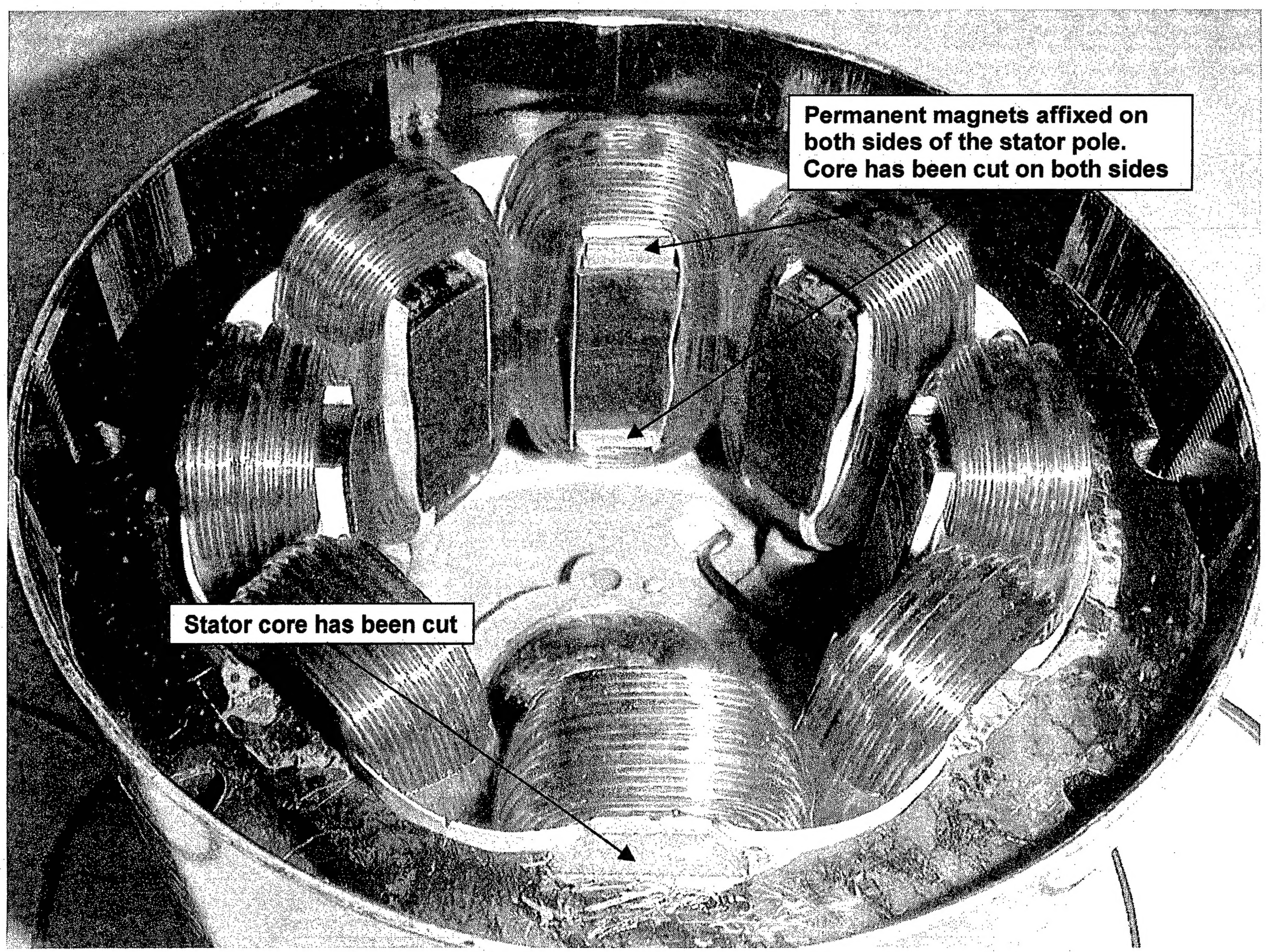

Figure A.3: *Self-excited generator design for which stator teeth have been cut, configuration #1*

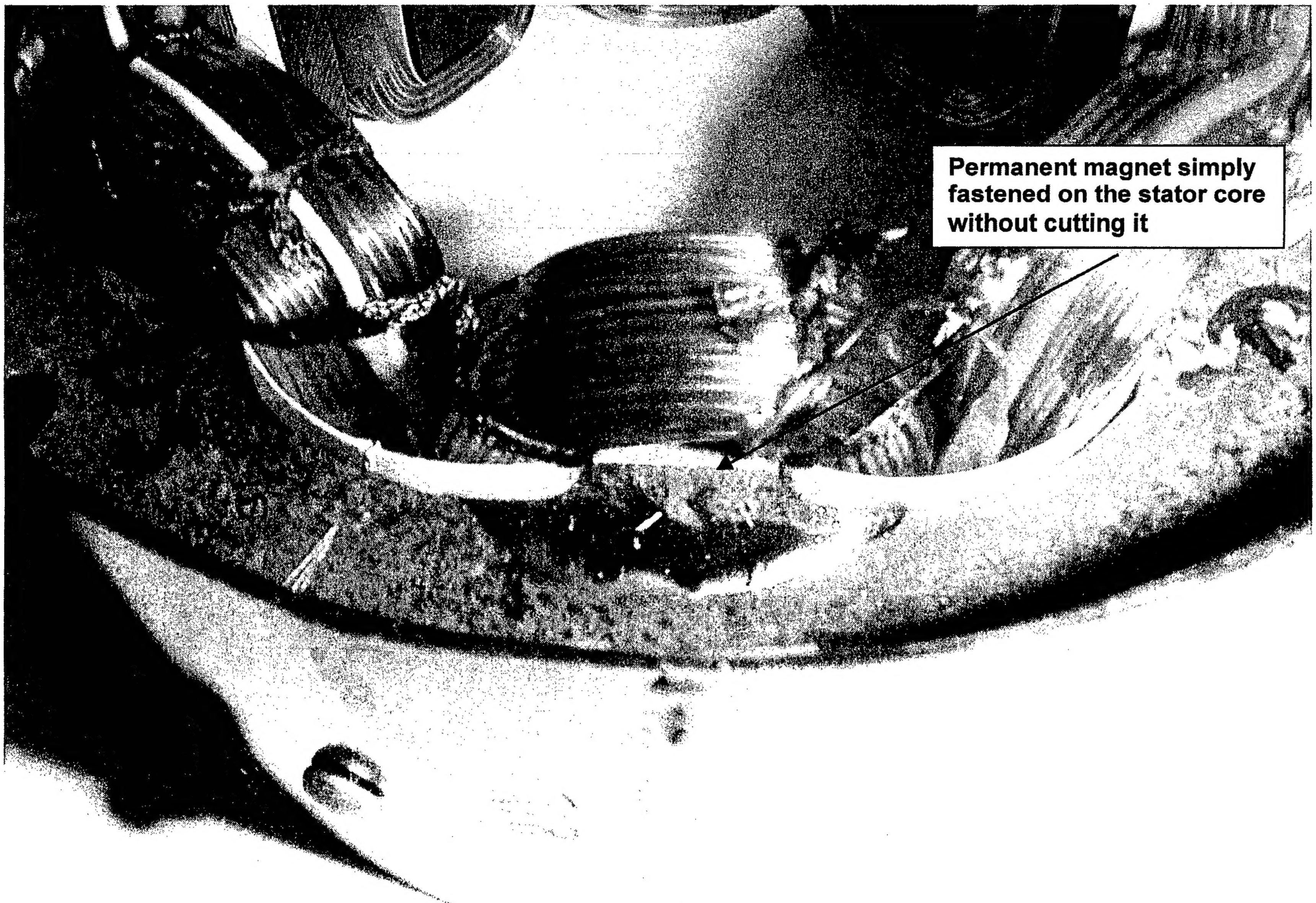

Figure A.4: *Self-excited generator design implemented without cutting the stator teeth, configuration #2*

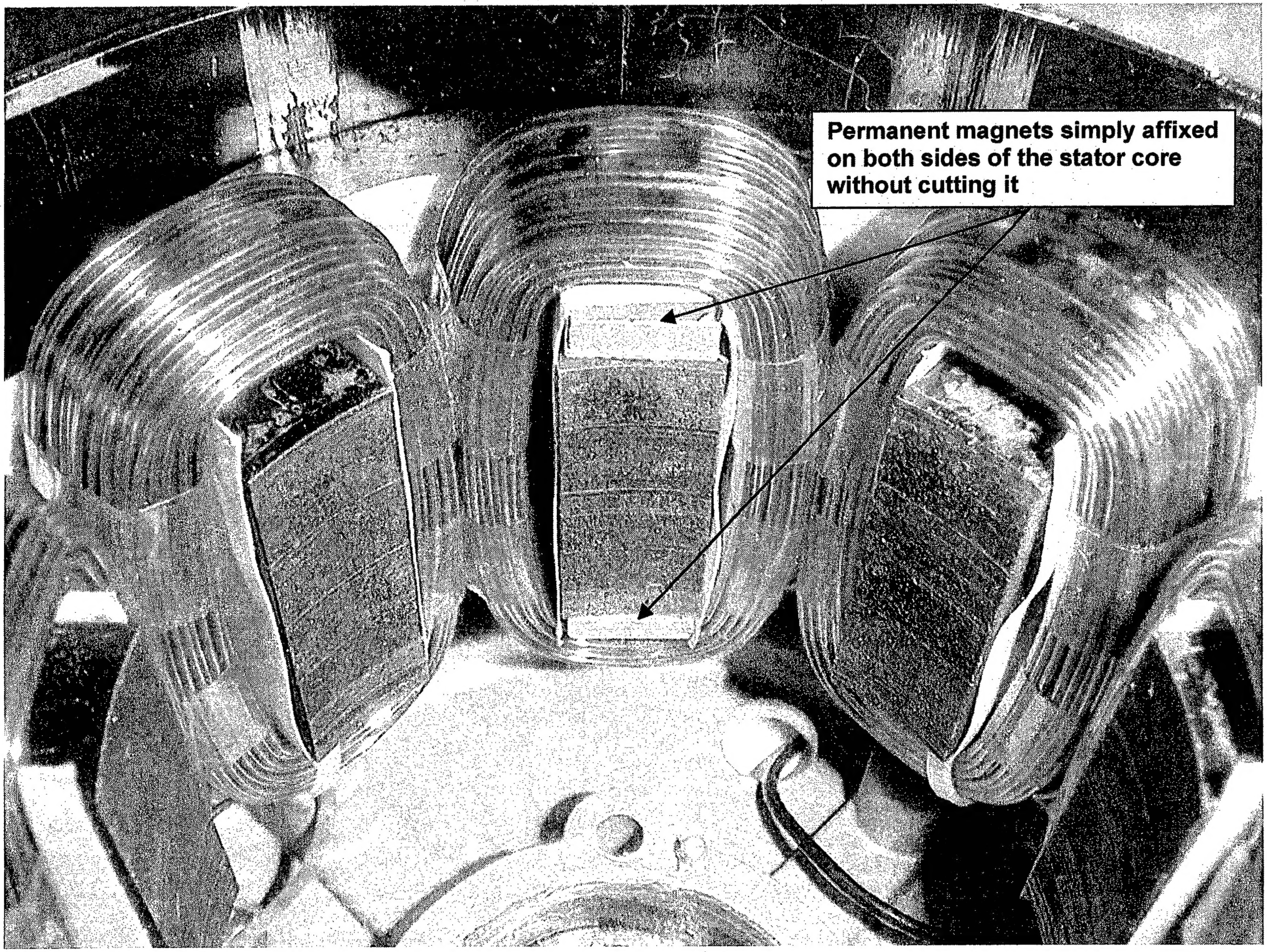

Figure A.5: *Self-excited generator design implemented without cutting the stator teeth, configuration #2*

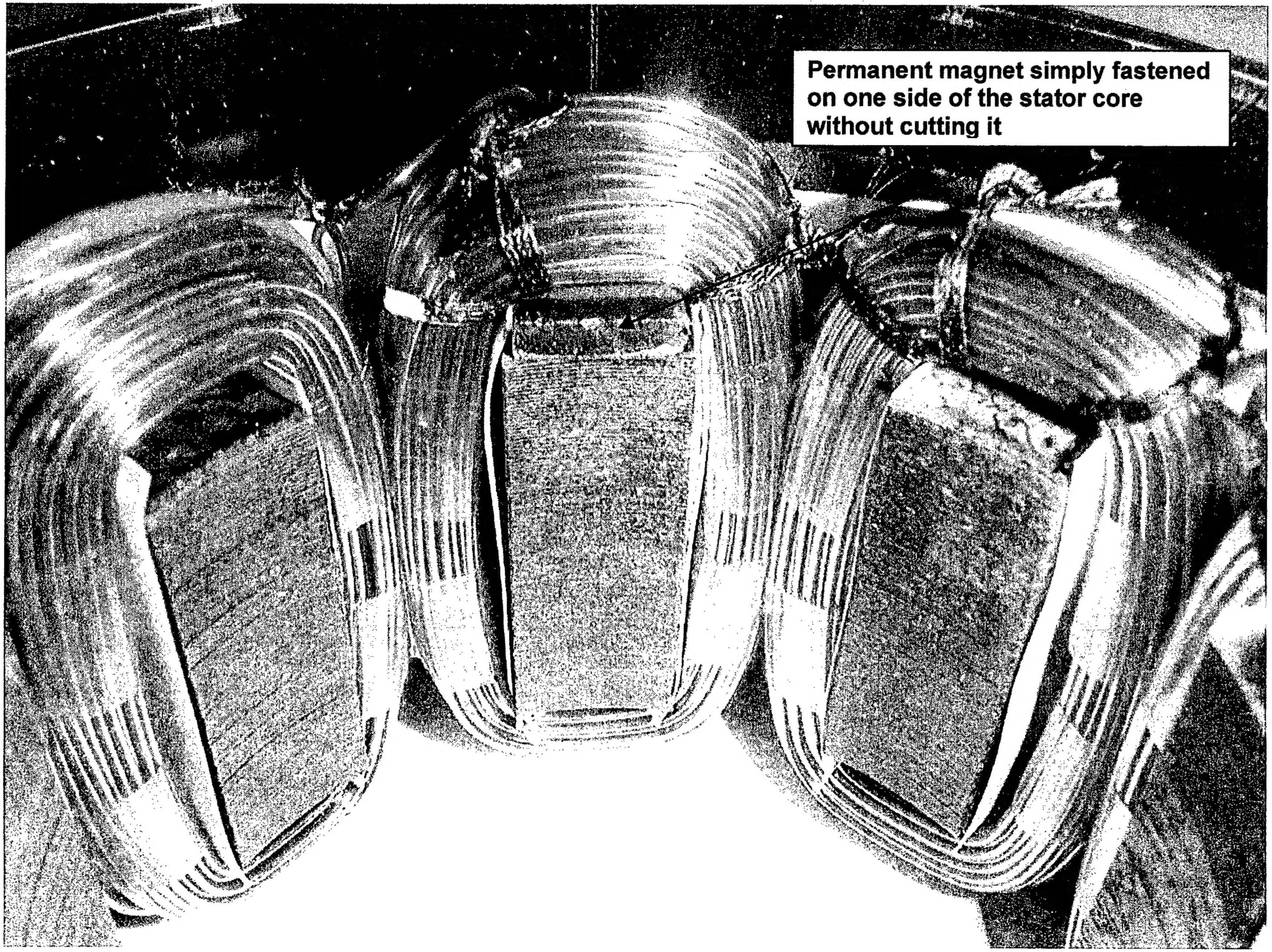

Figure A.6: *Self-excited generator design implemented without cutting the stator teeth, configuration #3*